A Null Test of the Metric Nature of the Cosmic Acceleration

Adeline Buzzi, Christian Marinoni, Sergio Colafrancesco

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A. Buzzi[1], C. Marinoni[1] and S. Colafrancesco[2,3]

[1]Centre de Physique Théorique, UMR 6207 CNRS-Luminy and Université de Provence, Case 907, F-13288 Marseille Cedex 9, France France
[2] ASI-ASDC, c/o ESRIN, Via G.Galilei, I-00040 Frascati, Italy
[3] INAF - Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio, Italy

E-mail: buzzi@cpt.univ-mrs.fr, christian.marinoni@cpt.univ-mrs.fr, cola@mporzio.inaf.it

Abstract.
We discuss the testable predictions of a phenomenological model in which the accelerated expansion of the universe is the result of the action of a non-gravitational force field, rather than the effect of a negative-pressure dark-energy fluid or a modification of general relativity. We show that in such a scenario the cosmic acceleration felt by distant standard candles like SNIa depends on the mass of the host system, being larger in isolated galaxies than in rich clusters. As a consequence, the scatter in the observed SNIa Hubble diagram has mostly a physical origin in this scenario: in fact, the SNIa distance modulus is increasing, at fixed redshift, for SNe that are hosted in isolated galaxies with respect to the case of SNe hosted in rich galaxy clusters. Due to its strong dependence on the astrophysical environments of standard candles, we conclude that alternative non-gravitational mechanisms for the observed accelerated expansion of the universe can be interestingly contrasted against the standard metric interpretation of the cosmological acceleration by means of an environmental analysis of the cosmic structures in which SNIa are found. The possible absence of such environmental effects would definitely exclude non-gravitational mechanisms as responsible for the accelerated cosmological expansion and will therefore reinforce a metric interpretation.

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1. Introduction

The unprecedent convergence of observational results we are presently witnessing has narrowed down the region of the cosmological parameter space which is compatible with all the different and independent probes of cosmology: Supernovae [1] [2], CMB [3, 4] and Large Scale Structures [5, 6, 7]. Robustly growing evidence suggests that *i)* ordinary matter is a minority ($\sim 1/6$) of all the matter content of the universe, *ii)* matter – mostly contributed by dark, non-baryonic matter – is a minority ($\sim 1/4$) of all the cosmological mass–energy density, mostly contributed by an obscure form of energy referred to as "dark energy", *iii)* the 3-D spatial geometry of the universe is flat and *iv)* the expansion of the cosmic metric is accelerating since the last $\sim$ 7 Gyrs of our universe lifetime.

Even though the big picture is in place, the two dominant contributions to the stress-energy tensor – i.e. dark energy and dark matter – have a still hypothetical nature and they have not been discovered yet. While there is widespread evidence for the existence of the non-baryonic dark matter component producing the potential wells of large-scale structures [8], yet no persuasive theoretical explanation has been able to elucidate the physical nature of the dark energy component [9]. As a matter of fact, unveiling the nature of dark energy and its role in cosmology and gravitation is a difficult and subtle challenge. In such a context, it shouldn't be overlooked that the large roaming from model to model, and the abundance of weakly predictive theories, might eventually limit the possibility to discriminate between different competitors proposed so far to explain the observed dynamics of the accelerating universe.

In the absence of a compelling theoretical explanation for the dark energy component, and in a minimal, zero-order approach, we explore here the possibility to preserve the standard metric interpretation of the accelerated expansion against possible alternative physical scenarios. To this aim, we first evaluate and then discuss the observable consequences of local, non-gravitational mechanisms which could in principle accelerate matter in our Hubble patch of the Universe. We assume here that the Universe is described by general relativity, it is dominated by components which satisfy the usual energy conditions (according to which the Universe can only decelerate) and that the onset of recent accelerated expansion is the result of the presence of an hypothetical non-gravitational force field. Such alternative explanation is rather conservative, since it assumes neither a cosmological constant (or negative-pressure fluid) nor a modification of general relativity. Accordingly, we first work out a self-consistent, non-geometric model for the cosmic acceleration that is able to reproduce the current observations of standard candles (i.e. SNIa) and then we discuss a falsifiability procedure aimed to test its observational predictions.

The motivation behind this work is to put strong limits to an hypothetical (or non usually considered) physics that is possibly missing in our picture of the universe, and, in turn, to strengthen the evidence supporting the standard paradigm with which we are currently explaining its past history, its present stage and its future fate.

2. Accelerated cosmological expansion with a non-cosmological, large-scale, radial force field

Our goal is to work out testable predictions that allows us to reject non-metric acceleration models. To this purpose, we construct here a general, phenomenological model in which the role of dark energy is mimicked by an alternative mechanism of non gravitational origin.

We consider here a background universe with a metric expansion as predicted by General Relativity. We assume that in such a universe an hypothetical large–scale, non-gravitational force field influences the overall dynamics of large scale structures in a patch of the universe with typical dimensions of the local Hubble volume. In this scenario every object which at time t sits on the shell of a sphere of proper radius $r(t)$ centered on the observer feels a peculiar acceleration field $\gamma_p(t)$ that is radially directed and time dependent.

We further speculate that the only cosmological component contributing to the stress-energy tensor is dark matter. In other words, we assume that there is no dark energy at all in the universe and that what we interpret as apparent isotropic acceleration of the metric is indeed the combination of the decelerated cosmological expansion predicted by General Relativity plus the Doppler effect sourced by matter which is accelerating outward under the effect of the radial force field we have added to this cosmological scenario.

In such a case, by appropriately tuning the non-cosmological contribution to the observed redshift, one can reconstruct a functional form for the luminosity distance d_L (see eq. 2 below) which reproduces the standard one derived within a model with cosmological constant (or dark energy): i.e.

$$d_L(z_{obs}, \mathbf{p}_{obs}) = d_L(z_c, \mathbf{p_c}, \gamma_\mathbf{p}) \ . \tag{1}$$

In other words, the standard ΛCDM cosmological parameter set (represented by the vector $\mathbf{p_{obs}}$) observationally inferred by simply plugging in the observed redshift z_{obs} into the luminosity distance formula are biased with respect to the *true cosmological* values (represented by the vector $\mathbf{p_c}$) that would be naturally inferred by recognizing the presence of a physical mechanism responsible for the acceleration of matter *in situ*.

Having outlined the phenomenological model we are pursuing, let us now elucidate its finer details, i.e. the dependence of the luminosity distance (Eq. 1) on the peculiar acceleration term γ_p.

The luminosity distance of an object standing at the observed redshift z_{obs} is given, in a pure matter scenario, by

$$d_L = (1+z_{obs})\frac{c}{H_0\sqrt{|\Omega_k|}} S_k\Big[\sqrt{|\Omega_k|}\int_0^{z_{obs}} \frac{dz}{E(z)}\Big] \ , \tag{2}$$

where $\Omega_k = 1-\Omega_m$, $S_k(x) = \sin(x)$ (if $k=1$), $S_k(x) = x$ (if $k=0$), $S_k(x) = \sinh(x)$ (if $k=-1$), and $E(z) = [\Omega_m(1+z)^3 + \Omega_k(1+z)^2]^{1/2}$.

While in the standard model the measured redshift z_{obs} has a pure cosmological interpretation, in the accelerated model it additionally includes the contribution of the peculiar velocity v_p induced by the radial non gravitational field and it can be written as

$$z_{obs} = z_c + \frac{v_p}{c}(1 + z_c). \tag{3}$$

Clearly, there is an infinite variety of cosmological models that, when combined with an equally arbitrary variety of radial acceleration fields γ_p, could in principle reproduce the observational features of the standard cosmological model. So, for the sake of simplicity, and in order to capture the essential physics of the problem, we assume in the following that the universe is flat, that its total density is contributed only by matter $\Omega_0 = \Omega_m = 1$ and its expansion rate is $H(z) = H_0(1 + z)^{\frac{3}{2}}$.
Under these hypotheses, the luminosity distance can be written as

$$d_L(z_c, v_p) = \frac{2c}{H_0}\Big\{\Big(1 + z_c\Big)\Big(1 + \frac{v_p}{c}\Big)\Big\}\Big\{1 - \Big[(1 + z_c)\Big(1 + \frac{v_p}{c}\Big)\Big]^{-\frac{1}{2}}\Big\}, \tag{4}$$

nonetheless, we stress that these working assumptions do not influence the generality of the conclusions presented in §3: analogous considerations hold, in fact, for a low density universe, open universe (with, e.g., $\Omega_m \sim 0.2$).

We can now compute how a peculiar velocity v_p in this scenario depends on the peculiar acceleration field: $v_p = v_p[\gamma_p(t)]$ at a given cosmological redshift z_c.
Using the expression of the proper distance to a given coordinate, $r(t) = a(t)x(t)$, we obtain the expression of the acceleration $\gamma(t)$ by means of which a perturbed metric expands radially:

$$\gamma = \frac{\ddot{a}}{a}r + \frac{\dot{a}}{a}v_p + \frac{dv_p}{dt}\ , \tag{5}$$

where $v_p = a\dot{x}$ and the peculiar acceleration term is given by

$$\frac{dv_p}{dt} + Hv_p = \gamma_p(t)\ . \tag{6}$$

After transforming this equation from the time to the redshift domain, we find the general solution

$$v_p(z) = (1 + z)\Big(K - H_0^{-1}\int \frac{\gamma_p(z)}{(1 + z)^{7/2}}dz\Big)\ . \tag{7}$$

We model the peculiar acceleration term in this equation by means of a general, non-divergent polynomial function

$$\gamma_p(z) = \gamma_0 + \sum_{i=1}^{n} \gamma_i(1 + z)^{-i} \tag{8}$$

where γ_i are free parameters to be adjusted with the constraint given by Eq. 1. Note that in the absence of a peculiar acceleration acting on cosmic matter, we recover the standard result that any primordial peculiar velocity is damped by the background expansion (i.e., $v_p \propto a^{-1}$).

2.1. Fitting the data

We show here that by appropriately tuning the parameters γ_i we can match the luminosity distance d_L of standard candles like SNIa as inferred within the standard model of cosmology.
To this aim, we first set the integration constant $K = 0$ by imposing that, in the limit $z \to \infty$, the peculiar velocity $v_p = 0$. We also set $\gamma_0 = 0$ in order to avoid any primordial acceleration field. Then, we fit Eq. 2 to reproduce the currently available supernovae data. We find that even a flat, matter–dominated $\Omega_m = 1$ cosmological model, when supplied with an appropriate local acceleration field, would be able to reproduce the luminosity distance derived by fitting the observed data assuming ("*wrongly*") a cosmological origin of the source redshift (see Fig.2).

We obtain an acceptable fit ($\chi^2_\nu \sim 1$) by expanding up to order $n = 4$ in Eq. 8. The best fitting coefficients in the redshift range $0 < z < 1.7$ (for a background cosmological model with $\Omega_m = 1$) are: $\gamma_1 = 3.20(\pm 0.06) \cdot 10^{-8}\mathrm{m/s^2}$, $\gamma_2 = -1.35(\pm 0.03) \cdot 10^{-7}\mathrm{m/s^2}$, $\gamma_3 = 1.81(\pm 0.04) \cdot 10^{-7}\mathrm{m/s^2}$, $\gamma_4 = -7.84(\pm 0.21) \cdot 10^{-8}\mathrm{m/s^2}$.

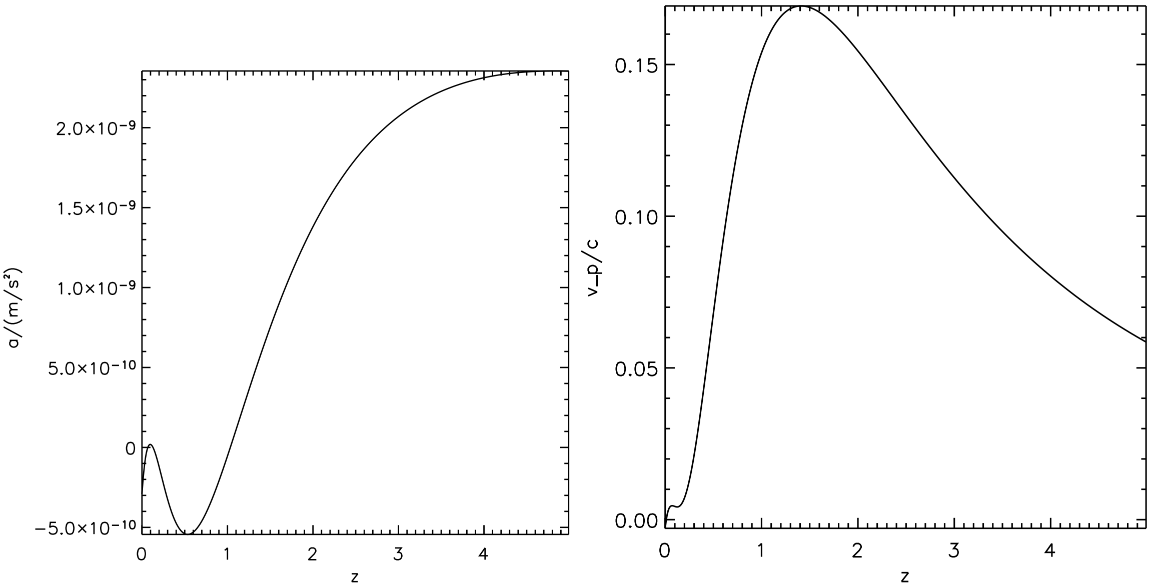

Figure 1. The best fitting peculiar acceleration γ_p *(left)* and peculiar velocity v_p *(right)* needed to reproduce current SNIa data (in the redshift range $0 < z < 1.7$) are shown as a function of redshift in a flat, decelerating $\Omega_m = 1$ background cosmology.

We find that the large scale peculiar acceleration required to fit the SNIa data (see Fig.2) is negligible with respect to other local acceleration fields. Given the smallness of its amplitude, it modifies almost indetectably the inertial nature of the reference systems to which it is applied at high redshift. Note that, in general, this is the order of magnitude of any large-scale, peculiar acceleration field one needs to introduce in order

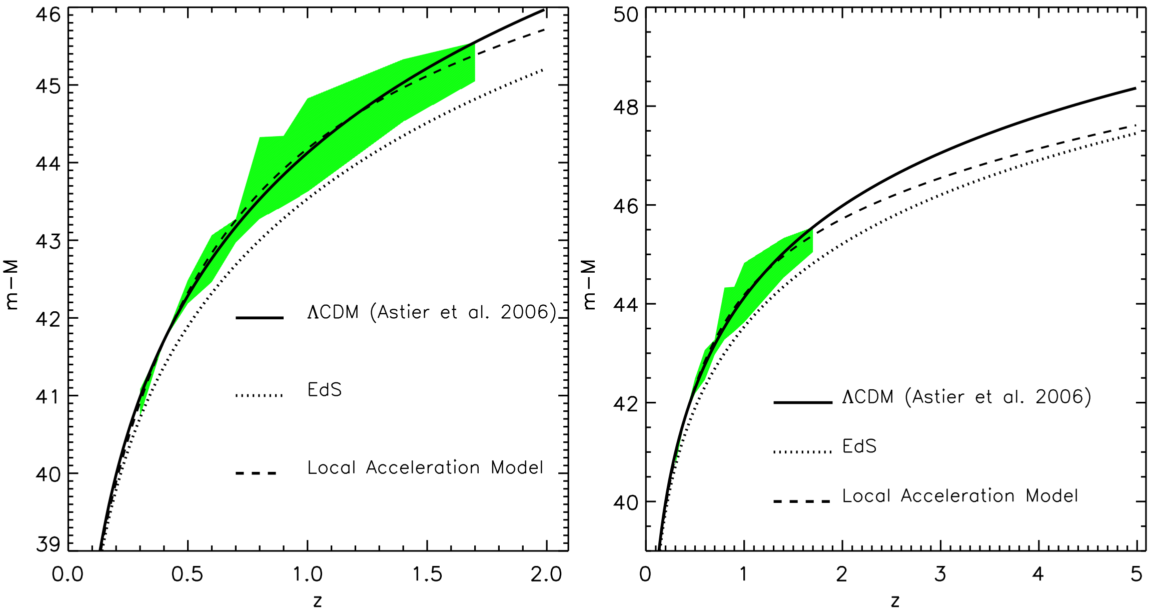

Figure 2. *Left :* the SNIa distance modulus is shown as a function of redshift for different cosmic expansion models: the best fitting ΛCDM model obtained by using distant supernovaes [11] (solid), a decelerating Einstein deSitter model (dotted) and a model in which a large scale peculiar acceleration field acts on top of the EdS world model (short-dashed curves). The shaded area shows the state-of-the-art dispersion in the observed SNIa samples from the SNLS collaboration [10] and from the HST gold sample [11]. *Right :* We show the convergence, at high redshift, of the peculiar acceleration model to the underlying background cosmological model (an Einstein de Sitter model in this case).

to re-interpret SNIa data over the redshift range $0 < z < 1.7$. For $z \to \infty$, the distance modulus predicted within this paradigm converges to the standard behaviour expected in the underlying, decelerated, cosmological model because the peculiar perturbation vanishes at early epochs.

We stress here that, by definition, the acceleration induced by such an hypothetical non-gravitational force should act differentially on the baryonic and non-baryonic matter components. Therefore, any possible non-gravitational accelerating mechanisms is physically viable only if it does not destroy (e.g., by segregating it in parts) the astronomical object onto which they act (for instance, by segregating the dark matter halo from the luminous baryonic component hosted within it). In other words, the acceleration time scale τ_{acc} in a cosmological frame has to be much larger than the typical dynamical time scale τ_{dyn} of a system trapped inside a dark matter halo.
By inserting the time-averaged value of Eq. 8 ($\langle\gamma_p\rangle \approx 5.7 \cdot 10^{-10} ms^{-2}$, if $\Omega_m = 1$) into Eq. 5 and solving by using $v_p = a\dot{x}$, we obtain hence

$$\tau_{acc} \equiv \left[2.9\frac{RH_0^{2/3}}{\langle\gamma\rangle}\right]^{3/4} \approx (G\rho)^{-1/2} \, , \tag{9}$$

where R is the comoving radius of the dark matter halo assumed in virial equilibrium, and ρ is its mean density. This simple physical argument puts stringent constraints on the viability of such a class of models. Unless one is willing to consider non standard model of gravity sourced only by baryons [e.g., MOND (Milgrom 1983) or TeVeS theories (Bekenstein 2004)], or yet unexplored interactions mediated by the dark matter particles, one can use the previous argument to set strong concerns on the physical reliability of such non-gravitational acceleration mechanism. Moreover, models of non-cosmological acceleration that are able to reproduce the metric acceleration without invoking the effect of dark energy are not positively defined over all the epoch of cosmological interest. Specifically, to explain the acceleration of distant standard candles without violating local constraints, one would need to invoke an acceleration of opposite sign at low and high redshift (see the left panel of Fig. 1). Additionally, these models yield also quite high peculiar velocities, which can even be of the order of a tenth of the speed of light at a characteristic epoch of $z \sim 1 - 2$ (see the right panel of Fig. 1). In principle, the strong sensitivity of the value of the large-scale peculiar velocity in such scenarios can also be used to put constraints on the viability of the non-gravitational acceleration models. We will see in the next session, however, that a crucial observational test can be devised to reject such non-gravitational acceleration mechanisms.

3. Testable predictions

We discuss here the observable effects that an hypothetical non-gravitational force field, say a "*dark force field*", should have on the global expansion of the Universe, as traced by a set of distant standard candles (e.g., SNIa). We show that the physical imprints of such a *"dark force"* can be unanbiguously contrasted with those of a *"dark energy"* component. In particular, it is possible to discriminate between them directly in the Hubble Diagram rather than, as usually done, in the equation of state parameter space. Indeed, if such a non-gravitational, radial force field exists (see, e.g., the preliminary suggestion that a large-scale magnetic tension might mimic the effects of dark energy [14], or the equivalent proposal of a large local void [15]), we can show that it accelerates cosmological objects (test particles) at the same radial distance in a different way. In fact, since only the gravitational force has the property to depend on the gravitational mass – which via the equivalence principle is equal to the inertial mass – it follows that, in the proposed "*dark force*" scenario SNe are not inertial systems in free-fall along geodesics of the space-time. The acceleration of SNe will thus have a unique signature: it will depend on the mass of the hosting system. Since in this *dark force* scenario the luminosity distance d_L of a cosmic object depends on its acceleration (see eq. 4 and 7), the different inertial masses of the test particles will cause predictable deviations from the mean, best fitting curbe shown in the left panel of Fig. 2.

One can parametrize the mass dependence of the peculiar acceleration experienced by a given system γ_p^* in terms of the best fitting mean acceleration $\bar{\gamma}_p$ using a simple scaling law

$$\gamma_p^* = \left(\frac{\bar{M}}{M^*}\right)^{\alpha} \bar{\gamma}_p \tag{10}$$

where the exponent α characterizes the specific physical mechanism responsible for the acceleration of supernovae. The limiting case $\alpha = 0$ describes the action of the gravitational field showing that, in this case, the acceleration of test particles is mass-independent. On the contrary, the acceleration generated by non-gravitational force fields is generically described by setting $\alpha \neq 0$. In particular, the case $\alpha = 1$ illustrates the large class of force fields in which the acceleration is inversely proportional to the mass of the test particle (for example models in which the strength of the force is independent of the mass of the object experiencing the field).

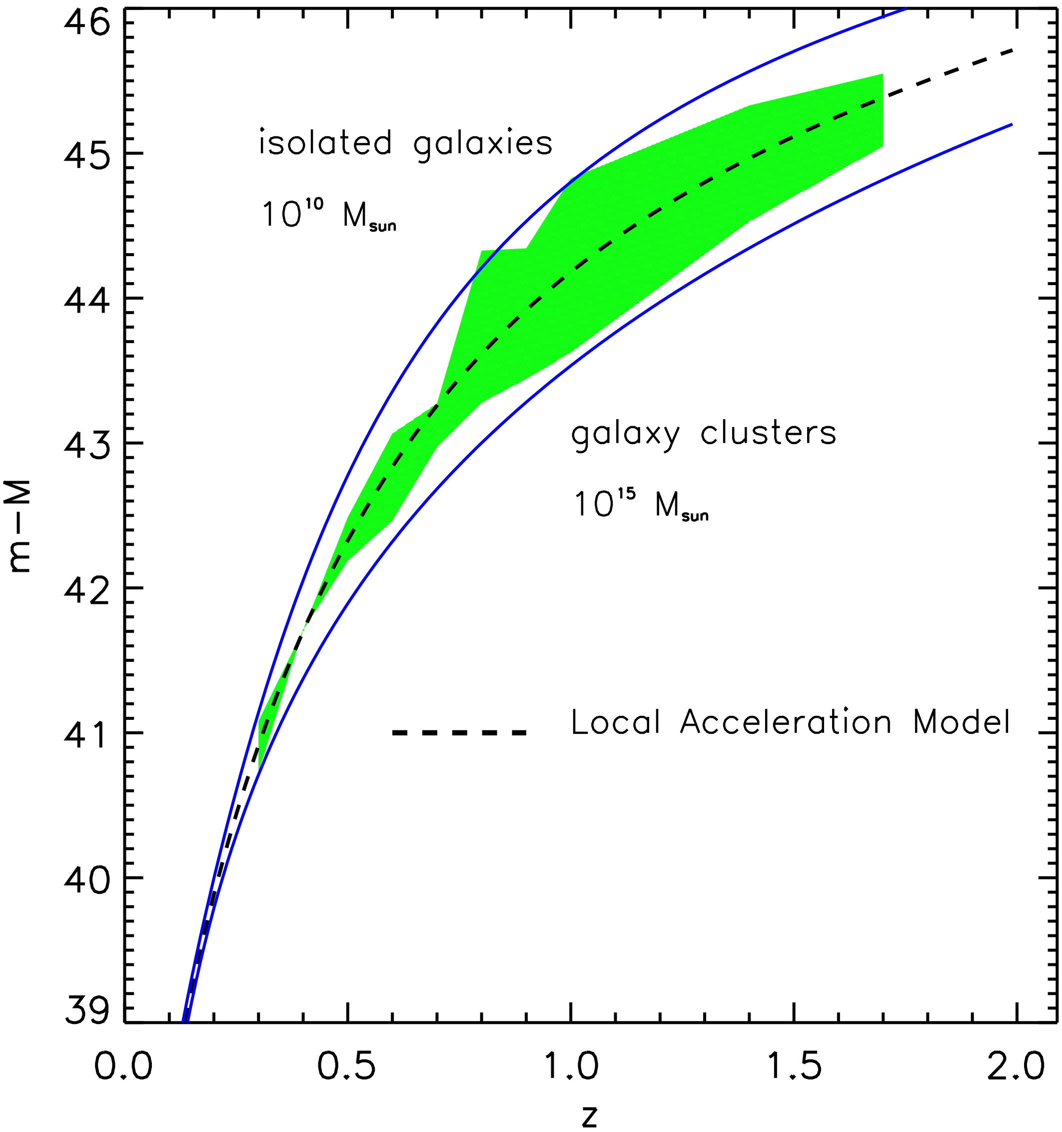

Figure 3. The SNIa distance modulus is shown as a function of redshift in the "*dark force*" scenario (black dashed curve). The lower (upper) solid curves bracketing the extremal envelopes of the dispersion in the Hubble diagram (shaded green area) are obtained by assuming $\alpha = 1$ in Eq. 10 and by letting the minimum and maximum mass of the test particles (SNe host systems) vary over over 5 orders of magnitude i.e., from normal isolated galaxies to galaxy clusters.

For the sake of simplicity let's discuss first the case $\alpha = 1$. A direct consequence of this assumption is that, at fixed redshift, SNe hosted in isolated normal galaxies (with typical mass of $\sim 10^{10}h^{-1}M_{\odot}$), when subject to the force field we are challenging here, will experience an acceleration of order $\sim 10^5$ stronger than SNe hosted in rich galaxy clusters (with typical mass of $\sim 10^{15}h^{-1}M_{\odot}$). (We assume here that the masses of the host systems remain constant with time). This effect systematically shifts the distance modulus of SNe in low (high) mass hosts towards higher (lower) values with respect to the reference, best fitting curve characterizing supernovae hosted in some fiducial system of mass $\bar{M}$ (see Fig. 3).

Similarly, without loss of generality, we find that for all the values $|\alpha| \gtrsim 0.1$, (i.e. even in the extreme cases of an acceleration field which has a weak dependence on the host mass), the family of distance moduli associated to SNe hosted in systems whose mass differs up to 5 orders of magnitude still spans the whole dispersion region characterizing current data. The systematic deviation from the best fitting relation of the distance moduli of supernovae hosted in a large variety of systems, going from small to large masses, is therefore practically insensitive to the exponent α parameterizing the mass dependence of the acceleration felt by supernovae. This general result follows from the fact that a) the distance modulus calculated by including the peculiar acceleration term cannot be smaller than the one computed in the associated background cosmological model, and b) to each value of the exponent α one can always associate an opportunely tuned value of the fiducial mass in the range $10^{10} < \bar{M}/M_{\odot} < 10^{15}$ in such a way that a change of 5 order of magnitude in the mass of the host gives distance moduli which are always confined between the upper and lower envelopes of the dispersion in the SNIa Hubble diagram.

Therefore, we conclude that in a *dark force* scenario, part of the scatter in the SNIa Hubble diagram has a physical origin: for a fixed redshift z and $\alpha \gtrsim 0.1$ ($\alpha \lesssim -0.1$), SNIa with larger values of $m - M$ in Fig. 3 should be hosted in small (big) systems, while SNIa with smaller values of $m - M$ should be hosted in rich clusters (isolated normal galaxies).

To summarize, a null-test of the metric nature of the accelerated expansion can be easily performed by means of an environmental analysis of the cosmic structures in which SNIa are found. Such a study could be optimally performed by future large-area sky surveys of distant SNe such as SNAP [16]. The strong sensitivity to the host system mass of the test strategy we suggest here will allow to exclude any hypothetical non-metric large-scale interaction which could be in principle responsible of the observed kinematics of the universe. Such a result would hence shed a much clearer light on the nature of the assumed Dark Energy component dominating the late stages of the cosmic evolution.

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